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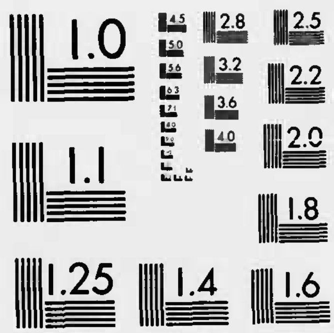
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ENGINEERING ASSESSMENT OF TEG AND TEG/FC TECHNOLOGY GROWTH POTENTIAL

FINAL REPORT

PHASE I
ENGINEERING ASSESSMENT OF EXISTING THERMOELECTRIC GENERATOR TECHNOLOGY

to

SYSTEMS ANALYSIS DIVISION
PROGRAMS AND ANALYSIS DIRECTORATE
U.S. ARMY MOBILITY EQUIPMENT RESEARCH AND DEVELOPMENT COMMAND
FORT BELVOIR, VIRGINIA 22060

CONTRACT NO. DAAK70-79-D-0036 TO 0020

by

ARTHUR D. LITTLE, INC.
CAMBRIDGE, MA 02140

86452

SEPTEMBER 1981

Arthur D Little, Inc.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An analysis of the likely conformance of current thermoelectric generators to the Army SLEEP ROC is provided. A feasibility analysis of the thermoelectric generator as a means of providing electricity, heating and cooling to a typical mobile teletype terminal is given. Findings relative to the thermoelectric generator as a candidate for the SLEEP ROC and as a primary energy source for a teletype terminal are given.

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FOREWORD

This work was performed under the sponsorship of the U.S. Army Mobility Equipment Research and Development Command (MERADCOM). The work was performed by Arthur D. Little, Inc. of Cambridge, MA 02140, under T.O. 0020 of contract number DAAK70-79-D-0036. Mr. Roger G. Long and Mr. W. David Lee were the principal investigators. This report was prepared under the guidance of Mr. Leon Medler of MERADCOM as the Technical Point of Contact and Mr. K.J. Dean of MERADCOM as the Contract Officer's Representative.

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1.0 INTRODUCTION AND SUMMARY

The United States Army has a requirement for silent and portable electric generators for tactical missions and has conducted research and development programs on several technologies to meet this objective. Thermoelectric generators (TEG) and fuel cells appear to be the near-term candidates for these applications (though other technologies such as Stirling engines may satisfy these requirements in the future).

Arthur D. Little, Inc., has undertaken a two-phase study to examine thermoelectric generator and fuel cell technologies for silent electric power applications considering both near-term technologies and potential long-term developments.

1.1 PURPOSE

The objective of Phase I of this work is to perform an independent engineering assessment of existing TEG technology. In Phase II, thermoelectric and fuel cell generating technologies will be compared and the potential for future development of each technology will be assessed.

1.2 SCOPE OF WORK

The engineering assessment of existing TEG technology work in this phase concentrated on two tasks:

- *Task 1.* Determine the viability of the TEG technology as an alternative candidate to satisfy the 0.5 to 10-kW requirements of the SLEEP ROC.*

- *Task 2.* Evaluate the potential for the use of the thermoelectric generator in a combined total energy package applied to an actual field use (the AN/TSC-58 telegraph terminal and associated shelter). The combined total energy package using the thermoelectric generator was compared to diesel and gasoline generators currently used to supply the AN/TSC-58.

Phase II of this study will provide a 10- and 20-year projection of the possible enhancement of both the thermoelectric generator and fuel cell technologies. A comparative analysis of the two technologies will be made with respect to the critical issues related to field development. A report on Phase II will be submitted at a later date.

*SLEEP (Silent Lightweight Electric Energy Plant) ROC (Required Operational Characteristics).

1.3 OVERVIEW OF PHASE I REPORT

The SLEEP ROC details key features to which the thermoelectric generator is compared in this analysis. The primary specifications detailed in the SLEEP ROC [1]* are:

- performance under climatic categories 1 to 8 [2] and at elevations from 0 to 8000 ft,
- electrical performance to meet MIL-STD-1332B[3],
- size and weight,
- inaudible at 100 meters, and
- startup time features.

In addition, acceptable levels of reliability, availability and maintainability are implied. The SLEEP ROC identifies characteristics for the entire family of silent electric generators over the range of 0.5, 1.5, 3, 5 and 10 kW.

The ROC applies to a total power supply system that includes the generator and power conditioner as shown in Figure 1. Fuel efficiency of different technologies varies, and the amount of fuel which must be provided to maintain a given power output increase accordingly. The impact of the fuel requirements is important in determining the total delivered weight for a specified mission and in assessing feasibility for tactical operations.

The anticipated demand for silent electric generators is concentrated primarily in the 1.5- to 5-kW range (reported to be 90% of the units) with the predominance of usage for signal requirements such as a telecommunications terminal. The ROC does not specifically identify an expected application though one was chosen for this study to provide a focus for the evaluation. MERADCOM selected the AN/TSC-58 telegraph terminal for use in the Task 2 analysis of the feasibility of using the TEG in an integrated system to provide electric power, space heating and cooling for a specific mission. The AN/TSC-58 application provided a framework for looking at the design trade-offs of TEG in a combined energy application.

In Chapter 2 we review the principles governing the performance of the TEG. Chapter 3 evaluates the compliance of the TEG with the SLEEP ROC. In Chapter 4, we present the analysis of the feasibility of using the TEG in an integrated energy system for field use with the AN/TSC-58 telecommunications terminal. Chapter 5 summarizes conclusions and recommendations resulting from our analysis in this Phase I study.

*Numbers in brackets are references listed on page 50.

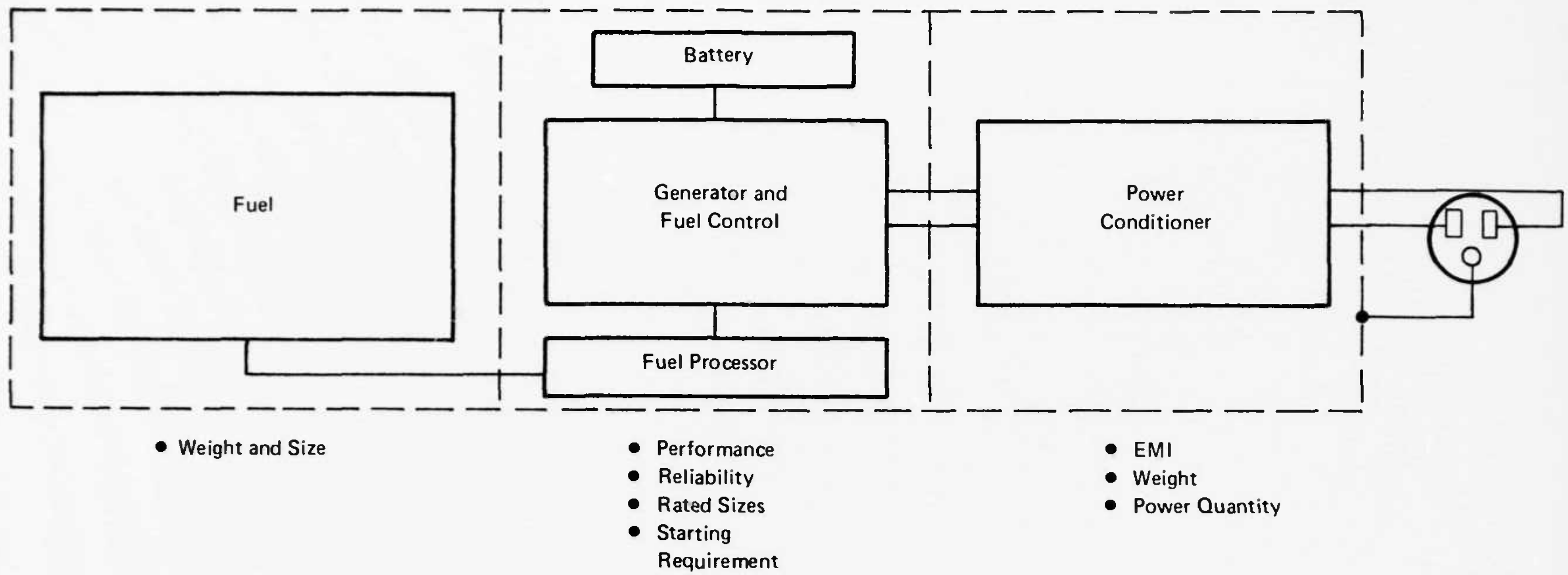


FIGURE 1 TYPICAL GENERATOR WITH POWER CONDITIONER

1.4 DEVELOPMENTS TO DATE — 500-WATT TEG UNIT

Development work on TEG's for Army applications began in the late 60's and continued at various funding levels. Table 1 summarizes the hardware development during this period and characterizes the generators by major technical attributes and manufacturer.

This analysis focuses on the anticipated performance of the new 6.3 breadboard model developed by Global Thermoelectrics Ltd. The unit has recently been delivered to Electronics Research and Development Command (ERADCOM) for testing, and test data are not available. It was necessary to estimate its performance by extrapolating from the earlier 500-watt units, taking into account the improvements that have been included in this model.

The new unit includes 288 thermocouple pairs, an increase of 12% over early models, to achieve the 500-watt rating at a higher ambient temperature (up to 52°C). A regenerative heat exchanger is used to lower exhaust temperatures and recover the waste heat, raising the expected overall power efficiency from about 3% to 4% overall [4].

1.5 POTENTIAL TEG SLEEP FAMILY

From discussions with ERADCOM staff [5,6] we understand that larger TEG capacities may be achieved through multiples of unit modules. One approach described would be a family made up of assemblies of 1.0 kW basic units. Such configurations would probably have a lowered reliability because of the multiple modules required. A more recent design approach has been discussed that would use a maximum of two modules for each size grouping. The basic modules would be designed as 0.5, 2 and 6-kW units to be arranged in groupings of two to achieve 1, 4 and 12-kW systems in terms of gross power. If this concept can be achieved, then a more satisfactory system configuration and more reliable design may be achievable. Multiple fuel supply systems are anticipated for the 3-kW and 10-kW units, raising the probability of failure. The present availability of the single 500-watt unit is 99.6, the projected availability of the 10-kW unit is 99.4, which is quite close to the desired level of 99.5 [7]. Larger TEG units may require the consideration of liquid cooling to achieve compact packaging of the modules or multiple air-cooled stacks (Figure 2).

TABLE 1

PAST AND PRESENT 500-WATT TEGS

Manufacturer	3M	ET&DL #1	ET&DL #2	Global Thermoelectrics	6.3 Model
Model	PP6075 (XE)/U	Modified	Further modified	New series Breadboard	Prototypes
	Upright, no regenerator, no battery	Horizontal, no regenerator	Experimental, regenerator	Horizontal, regenerator complete with battery and small tank	
Units Delivered	Approx. 25 total (12 by 4/1/72)	1 modified	1 modified before 1979	1 June 1981	9 to be delivered Oct. '81
Weight kg (lb)	26 (58)[a]	30 (66)[b]		39 (85.4)	36 (80)
Size (cm)	44W x 44D x 63H	63W x 48D x 53H		75W x 52D x 52H	46.7 x 46.7 x 66 with frame
(inch)	17.2 x 17.2 x 25	25 x 19 x 21		29.4 x 20.6 x 20.6	18.4 x 18.4 x 26 with frame
Fuel cons. kg (gals)	1.32 (0.48)/hr	1.35 (0.49)/hr	1.01 (0.37)/hr gasoline	1.2 (0.44)/hr	1.13 (0.41)
Thermocouples	256	256	256	286	288
MTBF	960 hr (tested)	2000 hr (est.)		2000 hr (calculated according to MIL Hdbk. 217)	

a. Without leads, battery, fuel, or cable.
b. Probably same

Common characteristics
Output: 500W
Voltage range: 25-32V
Internal DC power: 640W
Cooling air exhaust temperature: 90°C
Flue gas temperature: 300°C

Source: 3M Data — Reference 8
ET&DL #1 — Reference 4
ET&DL #2 — Reference 4
Global Breadboard — Reference 9
6.3 Model — Reference 5,6

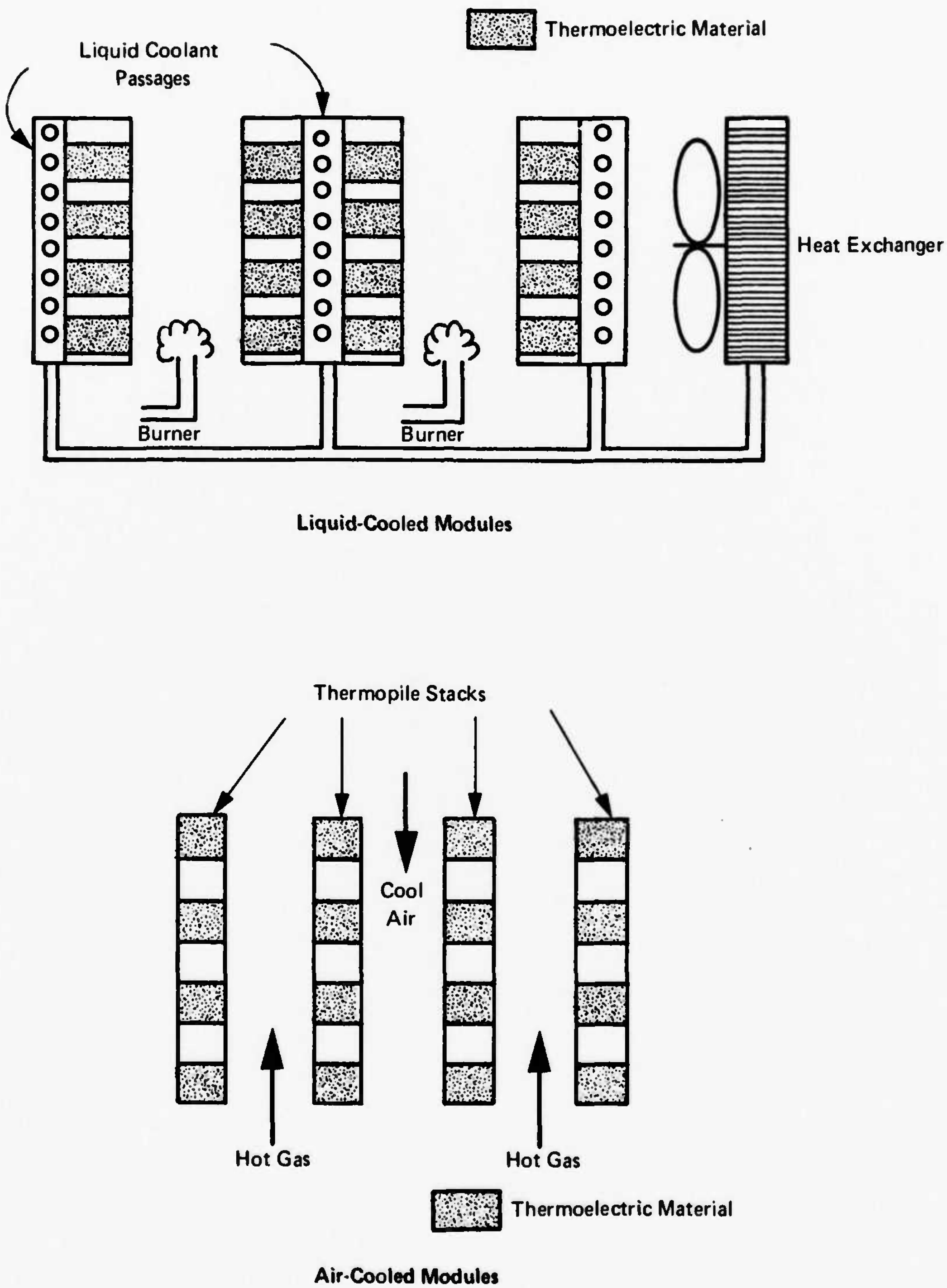


FIGURE 2 POSSIBLE TEG SLEEP FAMILY COOLING SYSTEM APPROACHES

1.6 SUMMARY OF PROJECTED CONFORMANCE TO SLEEP ROC

Tables 2 and 3 summarize our analysis of existing TEG technology based on the 500-watt Global (6.3) unit. The major issues raised are the non-conformance to SLEEP ROC in two areas.

- size (with frame) and weight requirements for an AC unit, and

- demonstrated Mean Time Between Failure in excess of 500 hours for OT (operational testing).

A 10-kW unit, based on the air-cooled lead telluride configuration used in the Global (6.3 model), would probably be 30 cu. ft.* without an inverter, which just meets the ROC specification for volume. With an inverter, the unit may exceed the ROC by 4 cu. ft. or about 13%.

Whether liquid or air cooled, the 5- and 10-kW units will exhaust 10 and 20 times as much heat as the 500-watt unit and will probably exceed the acceptable operational noise level.

In summary, extension of the present TEG technology to higher powers (10-kW) will be exceedingly difficult because:

Reliability -- multiple converter modules and individual fuel systems will raise the failure rate.

Noise — the large amounts of energy to be exhausted in cooling air may cause the 10-kW TEG to exceed the acceptable noise levels.

Weight — the 10-kW air-cooled lead telluride TEG will exceed the ROC weight level by approximately 100%.

*Based on 20 times the thermopile container size plus 10 times the blower/control/burner box of the new 6.3 model.

TABLE 2

PROJECTED CONFORMANCE OF 500-WATT GLOBAL (6.3) MODEL TO SLEEP ROC

Criteria	Ref. Paragraph of SLEEP ROC	Likelihood of Conformance
Time Frame (1978-1985)	2	1985-1990
Frequency 28 VDC	4-a	Certain
60 Hz AC		Certain, when developed
400 Hz AC		Certain, when developed
Rated Sizes 0.5 kW	4-a	Meets
1.5		Not applicable
3.0		Not applicable
5.0		Not applicable
10.0		Not applicable
Multi-fuel Capability	3.0	Certain, JP-4, DF-2, Gasoline
Time Between Shutdown and Recommitment (30 Min)	4-a	Certain
Reaction Time (15 Min)	4-a	Certain
Climatic Zones	4-b	Likely
High Altitude Performance	4-b	Likely
Electrical Performance	5-a	
AC		Certain
DC		Certain
RAM	5-b	Likely
Aural Non-detectability	5-c	Certain
Radio Frequency Interference	5-d	Certain
Lubricants	5-e	Not applicable
Transportable	5-e	Certain
Cooling System	5-f	Certain
Energy Storage and Electric Start	5-g	Certain
Battery Charging Suitability	5-h	Certain
Physical Characteristics	5-i	
DC		Likely
AC		Unlikely
IR Signature	5-j	Unknown

TABLE 3

PROJECTED CONFORMANCE OF TEG FAMILY TO SLEEP ROC

Unit Size (kW)	0.5	1.5	3	5	10
Time Frame to Feasibility (1985)	Certain	Likely	Likely	Unlikely	Unlikely
Output – DC	Certain	Certain	Certain	Certain	Certain
Output – AC	Likely	Likely	Likely	Likely	Likely
Multi Fuel	Certain	Certain	Certain	Certain	Certain
Maintenance Time	Certain	Certain	Certain	Certain	Certain
Startup Time	Certain	Certain	Likely	Likely	Likely
Ambient Temperature	Likely	Likely	Likely [1]	Likely [1]	Likely [1]
Ambient Air Pressure	Likely	Likely	Likely	Likely	Likely
RAM	Likely	Likely	Likely [1]	Likely [1]	Likely [1]
Acoustic	Certain	Likely	Likely	Unlikely	Unlikely
RFI	Certain	Certain	Certain	Certain	Certain
Lubricants	*	*	*	*	*
Transportable[1]	Certain	Certain	Certain	Certain	Certain
Cooling System	Certain	Likely [1]	Likely [1]	Likely [1]	Likely [1]
Battery Start	Certain	Likely	Likely	Likely	Likely
Size and Weight	Certain	Likely	Likely	Likely	Unlikely
IR	* *	* *	* *	* *	* *

Legend:

Predicted Conformance — Unlikely (small dot), Likely (medium dot), Certain (large dot)

* Not applicable

* * Unknown

[1] Anticipated development risk

2.0 BASIS FOR ANALYSIS OF TEG PERFORMANCE

2.1 THERMOELECTRIC PRINCIPLES

This section outlines principles of thermoelectric power production and specifically will treat the attainment of voltage and power characteristics of the SLEEP ROC.

A TEG is an assembly of thermocouples consisting of two legs of thermoelectric material as shown in Figure 3 and denoted by (N) and (P). Typically, the material is a semiconductor with the two legs doped N and P. When a temperature differential is maintained across the legs as shown, a voltage is generated and a current flows through the external resistance (R_o). The development of a voltage is a thermal physical phenomena known as the Seebeck effect. The thermoelectric material has a Seebeck coefficient defined as:

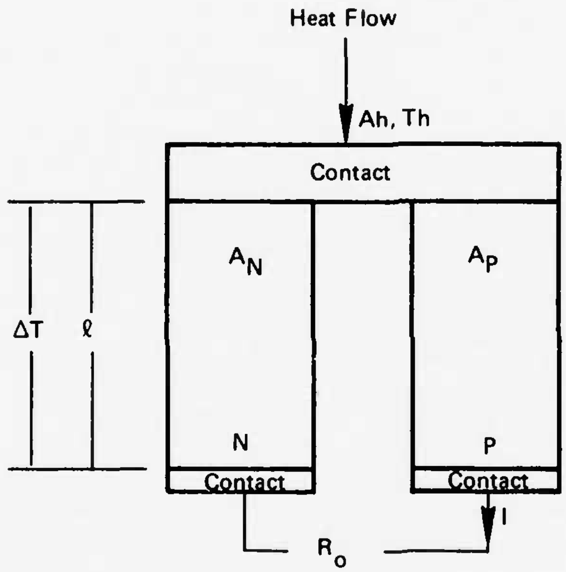
$$\alpha = \frac{dV}{dT} \text{ Volt/Degree} \qquad (1)$$

where: α = Seebeck coefficient
V = voltage
T = temperature

As the current flows through the legs of the thermoelectric device, secondary thermoelectric effects occur which govern the system performance. The Peltier effect occurs at the system junctions and amounts to a heat flow created by the flow of current. The Peltier effect is expressed as:

$$\Pi = \frac{\dot{Q}}{I} \frac{\text{Watt}}{\text{Ampere}} \qquad (2)$$

where: Π = Peltier coefficient
$\dot{Q}$ = heat flow
I = current flow



where:

ℓ = thermopile length

A = leg cross-sectional area

R_o = external load (resistance)

ΔT = temperature differential

FIGURE 3 ELEMENTS OF A THERMOPILE

and must be satisfied at the junctions. Similarly, a small but perceptible voltage is created on each leg of the TEG (homogeneous material) with the development of a temperature differential. This is known as the Thomson Effect and is expressed as:

$$\mathcal{T} = \frac{dV}{dT} \text{ Volts/Degree} \tag{3}$$

The Thomson coefficient and the Peltier coefficient are related to the Seebeck coefficient, and these factors can be combined in a figure of merit Z to describe the ability to produce power, where:

$$Z = \frac{\alpha^2}{RK} \text{ (degrees K)}^{-1}$$

where: α = Seebeck coefficient

R = total internal electrical resistance

K = total thermal conductance

The selection of thermoelectric materials is governed by Z and by the temperature limitations of the material. Materials with a high Z which can be operated at high temperature differentials (high temperature capability at the hot end) produce more power. The critical factor in TEG design is the identification of a material with a high Z value at a feasible operating temperature, T, and the value ZT at T is the most important determinant of TEG efficiency.

2.1.1 Voltage

The voltage of a TEG is governed by the Seebeck coefficient and the temperature differential maintained across the material. For lead telluride (used in Global units), a practical hot junction temperature is 565°C. The lower limit is governed by the cooling air temperature and is maintained at about 162°C. With lead telluride, this creates a thermocouple output of 0.11 volts DC. A series connection of 288 pairs will develop about 31.7 Volts DC.

2.1.2 Current

The current is governed by the Seebeck coefficient, the temperature differential, the internal and external resistance.

Analysis of the thermoelectric couple can be performed [10] to show the following relationship for current:

$$I = \frac{\alpha \Delta T}{R_i + R_o} \text{ Amps} \tag{4}$$

where: ΔT = temperature differential

R_i = internal resistance

R_o = external resistance

2.1.3 Efficiency

The maximum efficiency (η) of a thermocouple is governed by the following relationship:

$$\eta \text{ (maximum)} = \frac{\Delta T}{T_H} \; \frac{(1 + ZT_{av})^{1/2} - 1}{(1 + ZT_{av})^{1/2} + T_L/T_H} \tag{5}$$

The electric efficiency is governed by the ZT product and will effect the efficiency at the present unit operating temperatures as shown below:

Effect of ZT on Electric Efficiency

Hot End	565°C
Cool End	162°C

ZT	Electric Efficiency
0.2	2.8%
0.6	7.1%
1.0	10.3%
1.4	12.7%

2.1.4 Power

The power externally available from the TEG is found by combining the relationships for the temperature differential and the current and is shown as follows:

$$P = \frac{\text{power}}{\text{couple}} = \left(\frac{\alpha \Delta T}{R_i + R_o}\right)^2 R_o{}^* \qquad (6)$$

where: α = Seebeck coefficient

R_i = total internal resistance

---

*Maximum power occurs when $R_i = R_o$ and then $P = \dfrac{(\alpha\Delta T)^2}{4\ R_i}$.

The sensitivity of power to the Seebeck coefficient and the temperature differential is clearly shown.

For a given design and material, the electrical power output is proportional to the heat input which is proportional to the temperature differential and the total surface area of the heated and cooled junctions.

In summary, the voltage is determined by the temperature differential and Seebeck coefficient of the material used in the thermopile, while the current and power are related to the total heat flow.

2.2 CURRENT TECHNOLOGY

Properly selected thermoelectric materials used in pairs can produce power if a temperature differential is maintained across the pair and a means for conducting current to and from the thermocouple pairs provided.

2.2.1 Thermopile

A thermopile can be configured in a multitude of designs. Teledyne [11] utilizes an egg crate design of Bismuth-Telluride in which pairs are cast into molds. Global Thermoelectrics and 3M [5,8] use a configuration of slugs of thermoelectric material set in an 8 module section with spring loading of the slugs to provide thermal and electrical contact to and from the slugs. General Dynamics [4] has proposed a configuration of thermocoupled pairs set in a liquid-cooled tray array for a 100-megawatt design concept. While there are certainly other thermopile configurations of the thermoelectric pair, these three serve as broad examples of the variety of current thermopile design.

Selection of thermocouple materials is based not only on the consideration of power output and efficiency, but also on cost and fabrication limitations as well. Figure 4 shows the ZT coefficient product which, in combination with the known temperature differential, uniquely determines the thermal efficiency of the thermopile. Of the available materials, Lead Telluride offers good ZT values at an operating temperature of approximately 600°C. Lead Telluride will deteriorate significantly in air at these temperatures and must be confined in a hermetic environment that may be filled with a low-heat-conductivity inert gas such as argon or krypton. Global uses Lead Telluride in an argon-filled container in its current TEG designs. Silicon Germanium has the advantages of operating at a temperature of 900 to 1000°C, without deteriorating significantly in air, and does not require a sealed inert gas-filled environment. Several new proposed designs appear to be based on the use of a Silicon-Germanium approach or a Selenide-based system.

Electrical connection to the thermocouple element is an electro-mechanical contact that may be spring-loaded as in the Global unit or braze bonded as in Syncal units.

2.2.2 Heat Source

a. Army Developments

The Global TEG achieves temperatures approaching 590°C by using a forced combustion burner fueled by an ultrasonic atomizer for managing liquid fuels. A regenerative heat exchanger is used in this system to recover heat from the flue products, which are in excess of 565°C, and is used for preheating combustion air. A net thermal efficiency of close to the condensing limit of about 83% combustion efficiency could be achieved with the regenerative burner design.

b. Other Developments

A number of heat sources have been used to establish the hot junction temperature in other designs. Radioisotopes were used in several space and terrestrial applications. They offer a reliable lightweight source of heat but are not appropriate to the SLEEP application. Teledyne uses a catalytic burner for maintaining a relatively low temperature hot junction (300°C). The advantage of the catalytic burner is that it can be operated at excess air ratios lower than those of standard combustion units, thus improving the potential combustion efficiency (ratio of the useful heat to the heating value of the fuel input). However, the catalytic combustion units operate at a temperature less than that desired for an optimum ZT product as shown in Figure 4 and well below the temperature achieved by the Global unit. The catalytic combustor claims to offer improved flame stability and insensitivity to flameout or blowout conditions and is reported to re-ignite within 30 seconds of flameout. Current units are fabricated in low power ranges of less than 300 watts.

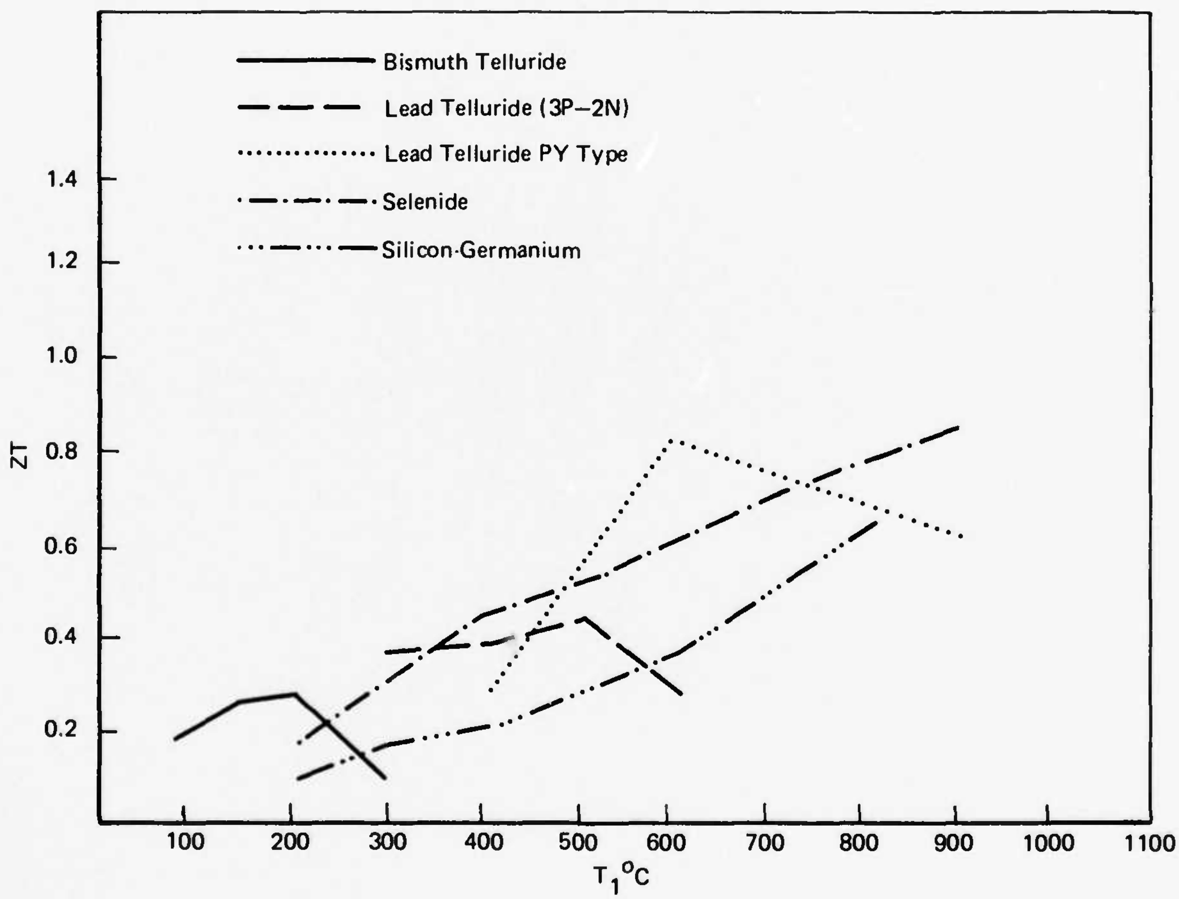


FIGURE 4 SAMPLE OF ZT VALUES FOR THERMOELECTRIC MATERIALS

2.2.3 Cooling

a. Army Developments

Heat must flow through the TEG for it to produce power and must be removed at the cold junction. In space or ocean applications, the ultimate source of cooling can be other than ambient air. The SLEEP application requires that the generator ultimately reject its waste heat to ambient air. Intermediate heat exchange from the hot junction to another heat transfer medium can be used to improve unit design layout for compactness or uniformity of heat distribution. Global employs a direct air heat exchange hot junction enhanced by an extended fin geometry. Some thermal resistance is experienced in the contact resistance between the thermoelectric slugs and the thermopile container. The effect of this resistance is probably insignificant. Air is convected over the extended fins with a high-speed vane axial fan operating with an electric motor which requires electric power from the thermopile and thus reduces its net output.

b. Other Developments

While other systems differ in configuration, they utilize the same fundamental principles as that employed in the Global unit. Teledyne uses the egg crate configuration in conjunction with a cooling fan for the 100- to 300-watt generator.

2.2.4 Power Conditioning and Controls

The principal control and power conditioning approach presently used in the Global unit is a DC shunt which maintains the desired voltage and allows the current output to vary with the load requirements. The thermopile operates at full output, and unneeded power is dissipated in the shunt resistance. While this system is effective in controlling power output, the energy dissipated in the shunt resistance is wasted and the fuel efficiency of the system could be improved by a more sophisticated electronic system for load control following. None of the present TEG manufacturers provide an AC output with a lightweight inverter package in use in many similar applications. This package converts the DC output to AC. The technology is considered within current state of the art but does add weight to the DC generator.

2.3 RELATIONSHIP OF 500-WATT GLOBAL UNIT TO AVAILABLE TECHNOLOGY

The Global unit is a fair representation of available fossil-fueled 500-watt TEG's. The Lead Telluride thermopile offers fair thermal efficiency, particularly when coupled with a high-temperature burner such as the ultrasonic atomizer for liqiud fuels used in the Global unit. It employs current technology for its cooling system and a regenerative heat exchanger. The present control and power conditioning units for the 500-watt Global unit could be improved by a design based on solid-state electronics for load control following. The current design does represent a practical approach for the load management requirements.

3.0 ANALYSIS OF SLEEP ROC CONFORMANCE

3.1 DATA SOURCES

A variety of data sources were used to develop the assessment of whether current TEG technology meets the SLEEP ROC. A literature search was performed and a synopsis of related referenes are given in the Bibliography. Specific sources of data or design information are cited in the text and are listed in the Reference section. Numerous telephone discussions were held with authorities in the field. Principal among these were discussions with MERADCOM and ERADCOM personnel, Layne Wilson of Global Thermoelectrics and Army staff at a number of locations. In-person interviews were conducted with: ERADCOM, MERADCOM personnel (in connection with inverter and AN/TSC-58 design), and Valvo Raag of Syncal. A review of present technology, summarizing recent General Atomics, Syncal and Teledyne designs, was undertaken through telephone conversations, analysis of available literature and a brief survey interview with Dr. John Roberts of Arco Ventures.

3.2 ENVIRONMENTAL PERFORMANCE

3.2.1 Description of the Global Unit

The TEG developed by Global for MERADCOM uses a liquid fuel burner for heating the hot junction and a fan for cooling the cold junction end of the thermopile. Air is the cooling medium so the cold end of the thermocouple will vary with cooling air temperature. The overall unit consists of thermocouple pairs set in an annular hermetically sealed can filled with inert gas. The inside of the can is heated with the products of combustion and the exterior is cooled with cooling air (ambient) passing over aluminum fins.

3.2.2 Temperature

The Global TEG is designed to maintain the hot junction at 565°C for the range of environmental conditions and the cooling fan is designed to maintain the temperature at the cold junction of 162°C at the design ambient temperature of 24°C. Active regulation of the hot junction is maintained by a feedback control system which directly adjusts the fuel flow. Active regulation of the cold side is not attempted. One of the major difficulties facing the designer of a TEG for use in a wide range of ambient conditions is that the thermal efficiency of most TEG materials is extremely low (under 5%); thus electric power of parasitic uses, such as the cooling fan, increase the fuel consumption and the size and weight of the package as well. Figure 5 shows the present level of parasitic losses for the Global unit. A high-speed cooling fan is employed to save size and weight, and the increases in fan air flow probably cannot be achieved without a substantial redesign of the unit (larger diameter, advance blade design). With a fixed air flow volume, the cold side of the junction will tend to vary with ambient temperature.

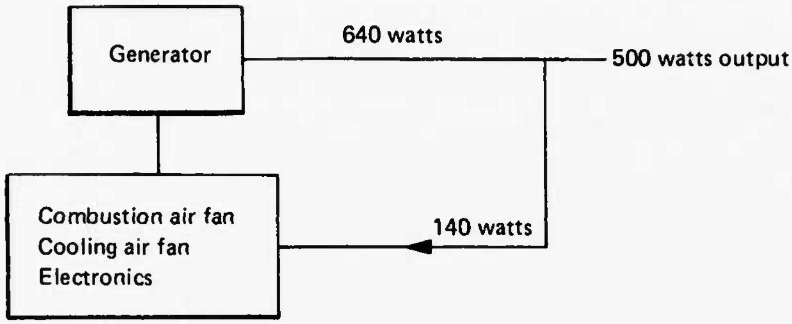


FIGURE 5 PARASITIC POWER REQUIREMENTS FOR GLOBAL UNIT

The effect of a change in ambient air temperature can be viewed from its effect on the heat flow through the junction which is proportional to the power generated. Equation 6 (Section 2.1) is used in a simple means of estimating this effect; this is done by differentiating the power generated with respect to the temperature difference ΔT.

$$dP = \left[\frac{2\,\alpha\,\Delta T}{(R_i + R_o)}\right] R_o \; d(\Delta T) \tag{7}$$

and divided by P where

$$P = \left(\frac{\alpha\,\Delta T}{R_i + R_o}\right)^2 R_o$$

we find

$$\frac{dP}{P} = 2\,\frac{d\Delta T}{\Delta T} \tag{8}$$

or

% change in power = 2 x % change in temperature differential.

A 50°F rise in ambient air temperature from 24°C to 52°C reduces the operating temperature differential by 6.8% and therefore power by:

% change in gross power = 13.7%

The gross power will be reduced as follows:

Gross power (24°C) = 640 watts
Gross power (52°C) = 552 watts

The parasitic power requires 140 watts. The predicted net output at 52°C is:

Net = 552 - 140 = 412 watts

which compares well with the reported value of 400 watts for the 3M PP 6075 unit, which was the predecessor of the Global 6.3 model.

The 500-watt rating at 52°C can be met by increasing the number of thermocouple pairs from 256 to about 290 (which has been incorporated in the new Global unit) and reducing the auxiliary electric consumption to 113 watts as outlined in Table 4.

TABLE 4

TEG ENVIRONMENTAL PERFORMANCE
(Watts)

	SLEEP ROC Required Minimum Power	Reported Performance of 3M PP 6075 256 Couples	Predicted Performance of Global 6.3 290 Couples
Elevated Temperature 52°C	500	400	500[a]
Elevated Altitude 8000 ft	450	425	529[b]

a. (400 + 140) 1.137 – 113 = 500.
b. (425 + 140 auxiliary) 1.137 – 113 = 529.

3.2.3 Pressure

Variation of performance with altitude (air density) is primarily due to the decline in air mass flow in the burner system. Some decrease in the cooling capability for the cold junction will also occur since the air density and, therefore, mass flow, will decline. The 3M data reports a 15% decline in power output versus an allowable 10% decline at 8000 feet [8]. Increasing the number of thermocouple pairs by 13% should allow the unit to meet tne evaluation criteria.

3.3 ELECTRIC PERFORMANCE

The specific electrical characteristics and the TEG performance, as related to MIL-STD-1332B, are summarized in Table 5.

3.3.1 DC Output

The primary power source of the TEG is the thermoelectric converter (thermopile) module, which is inherently a DC source. Its open circuit voltage (EMF) is proportional to the temperature differential between the hot and the cold junctions of the thermocouples. This differential can be controlled by adjusting the burner fuel rate.

TABLE 5

TEG POWER QUALITY WITH REFERENCE TO MIL-STD-1332B

	MIL-STD-1332B Requirement	TEG Performance
Regulation	4%	0.6%
Stability	2%	0.4%
Ripple	5.5%	0.4%
Voltage Adjustment Range @ Normal Temperature	23-35	25-32

Because the fuel control, which senses the EMF of the thermopile, cannot follow fast load changes, an electronic DC voltage reguator is provided in the TEG. Present designs employ a shunt regulator; i.e., a circuit that draws varying amounts of current in addition to the load of the TEG. Shunt regulators have unique advantages in this particular application: they are simple, and they keep the internal dissipation and the current in the thermopile constant. However, they do suffer from poor efficiency. Whenever the peak power demand drops, the shunt regulator absorbs the excess power until the setpoint of the fuel control loop is adjusted manually for minimum fuel consumption. When the power demand is near maximum, the shunt regulator consumes little power.

The fuel control loop of the present design (Figure 6) uses a control signal proportional to the converter EMF, i.e., to the temperature difference between hot and cold junctions. This is accomplished by measuring thermopile current (I) and voltage (E) and computing, in an analog circuit, the quantity EMF = E + IR_s, where R_s is the thermopile source resistance. This quantity is compared to a setpoint given by the (manual) "Wattage" control. The difference signal is used to drive the fuel pump. The fuel control circuit tracks the temperature difference across the thermopile to maintain a constant control loop from raising the hot junction temperatures too high. The result is a drop of available power output of about 3.6 watts/°C above 80°F [8]. No similar protection circuit was provided for high-altitude operation.

In practice, the operator sets the "Voltage" control to the desired operating voltage and then adjusts the "Wattage" control; i.e., the "Fuel" control, until there is some small excess power available beyond the expected peak demand. The excess is dissipated by the shunt regulator — at worst causing less than optimal fuel efficiency. Finally, the operator adjusts the combustion air fan with the "Blower" control until the flame appears to burn cleanly and efficiency.

An automatic power regulator might be a useful improvement, because one may expect many operators to set that control habitually to maximum. A slow optimization loop could take a signal from the shunt regulator and adjust the fuel control loop setpoint continuously to match the peak power demand of the last, say, ten minutes of operation. This would economize on fuel and always operate the converter as cool as possible.

Alternatively, a battery of sufficient capacity to supply, say, ten minutes of full power would permit the fuel loop to be adjusted for average rather than peak power. If more current were required, the fuel loop would respond in perhaps one or two minutes, while the battery supplies any excess demand during that time. Electronic circuitry would govern the distribution of charge and discharge between battery and thermoelectric converter and keep the terminal voltage constant. Such a scheme would provide ample starting capability and a stand-by capability to shut down the burner for a few minutes of maintenance. This may significantly increase its practical value by eliminating the need for a second generator in many missions. The battery would, in effect, improve the maintenance ratio and thus the availability of the TEG at some increase in weight and size.

3.3.2 AC Output

The TEG produces a DC output, and an inverter is necessary to provide sinusoidal AC power to meet the requiremnets of MIL-STD-1332B. Depending on the size of the generator, frequencies of 60 or 400 Hz and voltages of 120/240V single-phase or 120/180V three-phase are required in addition to the 28-volt DC units.

Inverter designs for this particular application must offer lightweight and high efficiency. The latter is vital to economize on the size of the required DC source and its fuel consumption as well as to limit the internal dissipation of the higher power inverters. The requirement of low weight generally rules out tuned circuits and

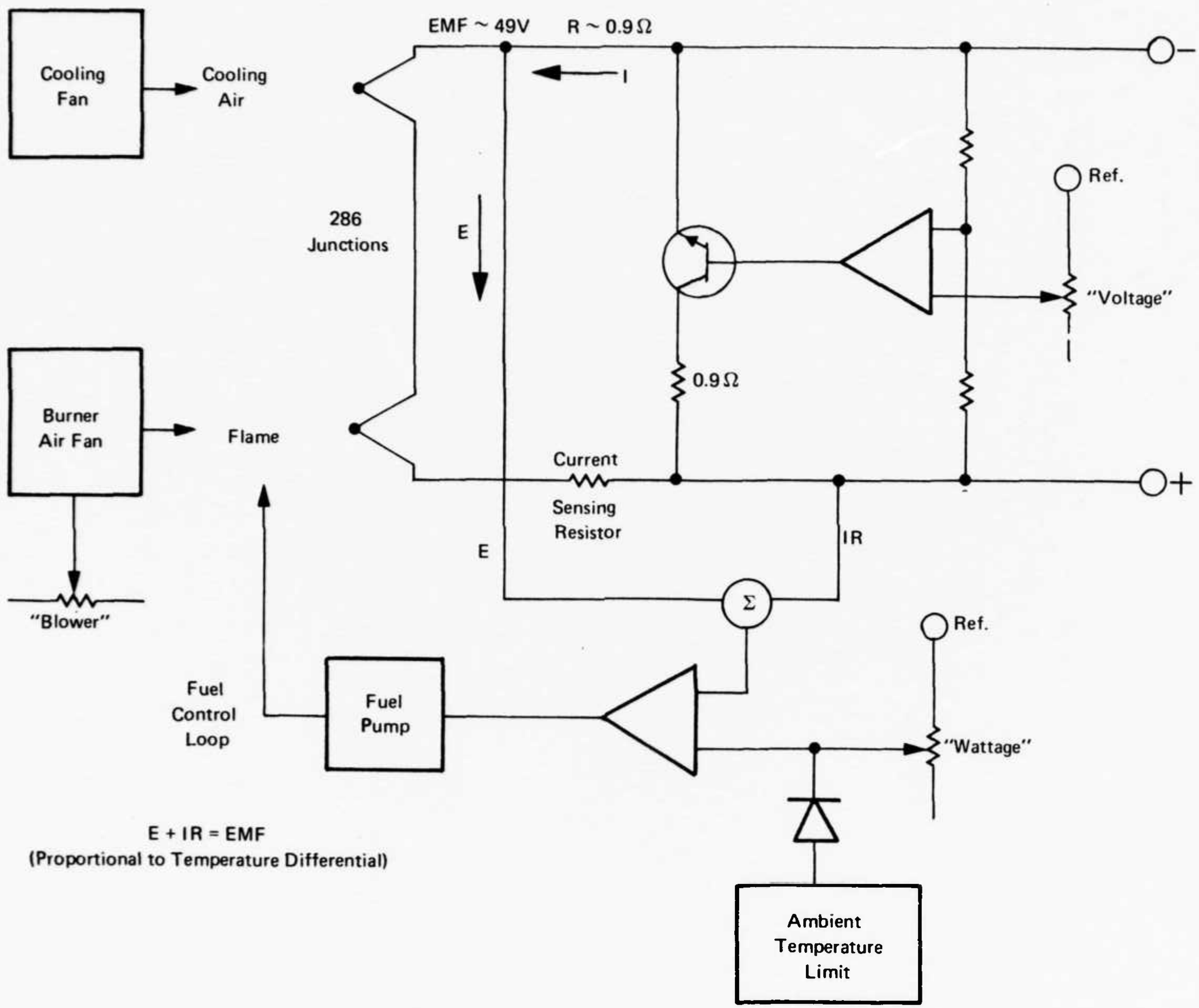


FIGURE 6 CONTROLS OF GLOBAL 500-WATT TEG

most transformers for operation at 60 Hz. Two design approaches to produce sinusoidal power are (1) by a step approximation to a sinewave which is formed by switching several DC supplies, and (2) by pulsewidth modulation at some fairly high carrier frequency. In both cases, low order harmonics are not generated, and a rather high frequency (and hence low weight) filter in the output suffices to produce a reasonably clean sinewave as required by MIL-STD-1332B.

The electronic details and the trade-offs involved in the design of such inverters are numerous. A full description and critical discussion are beyond the scope of this effort. However, these factors will ultimately determine the weight, efficiency and cost of future inverters. For a realistic estimate of the inverter technology presently available in practical units for the Army SLEEP program, we obtained data on design goals from the Electric Control and Analysis Branch of MERADCOM [9,12]. They are the results of recent R&D and form the basis of the table of inverter weights in Section 3.10. These inverters weigh 25-40 lbs/kW in fairly rugged packages. Commercial units for aircraft use are typically made for 20 to 32 volts DC input and single-phase 60-Hz or 400-Hz output, and weigh no more than 25 lbs/kW. The difference is readily explained by the easier packaging requirements and by the single-frequency, single-voltage output of the commercial units.

More recently, at least one manufacturer has offered a very much lighter unit for commercial aviation [13]. Their 14-pound, 1000-watt, 60-Hz inverter appears to meet all environmental, electrical and RFI requirements for our application. It is packaged for commercial aircraft use. In any case, it proves that a weight of 15 to 20 lbs/kW is a realistic goal for a development program.

The inverters on which Section 3.10 weight estimates are based are for input voltages of 40 to 60 volts DC. Thermoelectric converters could be designed to operate optimally in that same range of output voltages by increasing the number of thermocouples, or the present 28-volt types could be operated at less than optimum load.

Another solution would probably be a family of inverters, designed for a particular fixed optimum DC output voltage of TEG's. A more careful design study is likely to show that a combination of DC shunt regulator and constant input voltage operation of the inverter would best provide simplicity, optimum service life of the thermopile, and even for minimum weight and cost of the combination TEG and AC inverter. A constant input voltage is likely to simplify the AC inverter design sufficiently to compensate for the DC shunt regulator, while the waste heat output from the TEG is so large that the extra dissipation of a DC regulator would not appreciably increase thermal design problems.

Inverters become progressively simpler, more reliable, and more efficient as the input DC voltage approaches the output AC voltage. The optimum TEG for operating an inverter would thus have a much higher output voltage than the present nominal 28V DC. However, there are important trade-offs here: while the inverter problems are minimized by higher DC output, the TEG may require more junctions

in series and would be less reliable. Also, the DC output of a high-voltage thermopile is no longer readily compatible with standard Army requirements (MIL-STD-1332B) of 23-35V DC. Series-parallel switching of thermopiles could be employed, or straight DC operation could be replaced by rectification of the AC inverter output. These are questions for a comprehensive system design study.

3.4 MULTIFUEL CAPABILITY

The hot junction temperature is maintained with an ultrasonic fuel atomizer and forced air burner. The primary air volume can be adjusted manually, and the fuel flow is controlled automatically to maintain the desired temperature differential. With liquid fuels of similar physical characteristics (viscosity, heat content), the ultrasonic atomizer burner should operate effectively. Particulates in the fuel will clog the fuel system so proper filtering must be employed.

Performance tests of the burner with JP-4, gasoline and diesel fuel have been reported by Guazzoni [4] and showed satisfactory operation. We see no reason why the TEG system should not perform effectively with gasoline, JP-4 fuel and diesel as well as kerosene and summer diesel in the near future without substantial technological changes.

3.5 STARTUP AND SERVICE TIMES

The required operational performance times for the SLEEP application are 15 and 30 minutes, respectively, for startup and service times. We see no significant difficulties in the TEG meeting these reponse times.

3.6 RELIABILITY, AVAILABILITY AND MAINTAINABILITY

Reliability, availability and maintainability (RAM) are important factors for the SLEEP application. However, clear criteria for the SLEEP application have not been established for these factors. The following sub-sections describe an Arthur D. Little, Inc. interpretation of the SLEEP ROC application requirements for RAM.

3.6.1 Reliability and Availabilty

Reliability criteria identified inthe SLEEP ROC were to be derived from the Development Plan. This document was not available to Arthur D. Little, Inc. during the course of this study, though an analysis performed by Dr. Charles Leake [7], recommended an expected level of 500 hours Mean Time Between Failure (MTBF) for the acceptable reliability. In addition, Dr. Leake recommended 6 hours for Mean Time to Repair (MTTR) as well. Operational testing at Fort Huachuca [5] and Fort Bragg [14] demonstrated a measured MTBF of 57 to 185 hours. Component analysis by Global [15], based on MIL-HDBK-217, yields a projected MTBF of 1300 to 1500 hours. While a value of 950 hours was calculated by 3M from stationary tests [8], the MTBF of the TEG will probably be between the low values observed in early versions of the generator and the predicted reliability based on the the new designs.

Assuming an optimistic value of 1500 hours for the 500-watt unit, we present the other relevant reliability parameters in Table 6. Predicted availability of the 10-kW unit is based on an Electronics Technology & Devices Laboratory (ET&DL) procurement goal of 10,000 MTBF for the converter [5] and present failure rates for the power system and inverter.

TABLE 6

RELIABILITY, AVAILABILITY, MAINTENANCE FOR TEG

		Optimistic Predicted Performance of TEG	
	ROC[a]	500-watt	10-kW[b]
Mean Time To Failure (hours)	500	1500[c]	950
Mean Time To Repair (hours)	6.0	4[d]	4[d]
Regular Maintenance Period (hours)		1000[e]	1000[e]
Maintenance Time (hours)		1.5[f]	1.5[f]
Availability or Maintenance Ratio	99.5	99.58	99.4

a. USAES-CDE, C. Leake analysis of Development Plan Requirements.
b. Based on design information provided by ERADCOM, in which 2-6kW (gross power) units are used to provide the 10-kW net output.
c. Global April 1980 Monthly Progress plus 5000 MTBF estimate for inverter.
d. Arthur D. Little, Inc. estimate.
e. ERADCOM estimate.
f. Diesel filter change plus battery charge.

Operational testing (OT) will be required to determine reliability in a tactical environment. Experience with diesel and gas generators shows a substantial reduction in MTBF during operational testing. Comparable values of 10-kW diesel generators indicated a design value of 500 hours of MTBF with 3.4 hours MTTR. While the TEG may not demonstrate 1500 hours MTBF in real use, we see no loss in reliability over the present gas or diesel generators.

3.6.2 Maintainability

Based on the Fort Huachuca [5] and Fort Bragg [14] tests, there appears to be no apparent reason for the TEG not to meet maintainability requirements.

3.7 NOISE AND RADIO FREQUENCY INTERFERENCE (RFI)

3.7.1 Acoustic Noise

The noise data developed for the Global 6.3 model are shown in Table 7. Data were extrapolated from the test at five feet to the anticipated levels at 100 meters in

TABLE 7

THE TEG ACOUSTIC NOISE

Frequency (Hz)	ROC @ 100m	PP-6075[a] @ 5 ft	PP-6075[b] @ 100m	10kW Unit[b,c] @ 100m
63	35dB	66	26.6	39.0
125 and Above	20dB	67	29.9	43.0

a. 3M final report [8].
b. Bolt, Beranek and Newman estimates.
c. Assumes standard heat exchanger practice, 100 to 300 feet per minute air flow.

consultation with Bolt, Beranek and Newman [16]. The extension to the 100-meter distance represents a fairly reliable extrapolation and indicates that the 500-watt TEG could meet the noise specification of the SLEEP ROC with some acoustic treatment designed to lower the higher frequency noise levels.

Predicted noise levels for the 10-kW TEG exceed the inaudible criteria. Standard heat exchangers and fan design was assumed; and in order to meet the ROC noise levels, substantial design attention to noise would be required to meet the inaudible criteria. This can be done at some level of development risk.

3.7.2 Radio Frequency Interference

a. Present DC TEG's

The only TEG's that have been tested for RFI are the original ones built by 3M in 1972. In its final report, 3M demonstrated compliance with the radiated and conducted emission requirements of MIL-STD-461A. Somewhat marginally high levels were measured as radiated broadband emissions near 100 kHz.

The same units were tested again to MIL-STD-461A, by TECOM, U.S. Army Electronic Proving Grounds, in 1973. The items failed the radiated broadband emission test by 3 dB at 100 MHz and by 7 dB at 76 kHz.

The new units now being built by Global for ET&DL have so far not been RFI tested. According to Global, many improvements have been made in circuitry and packaging. The automizer drive circuit was redesigned to eliminate certain spurious modes of oscillation it apparently could assume before. It is the nature of RFI suppression work to have problems develop only in full-scale testing. However, we would expect Global's present efforts have improved the chance of the units to meet applicable RFI specifications from MIL-STD-461B.

b. Present AC TEG's

The more elegant and lightweight DC-to-AC inverter designs are by their nature rather prone to generate RFI. High carrier frequencies are employed to shrink transformer and inductor sizes, and fast rise times are necessary to hold down dissipation in the switches. The latter in particular will work towards generating and radiating high harmonics and towards conduction of RF noise to output and input of the inverter. However, these problems are universally recognized by competent manufacturers and are evidently not insolvable. Most commercial inverters meet at least some stringent RFI specification (FCC) and, in many cases, meet the present MIL-STD-461B. We foresee the need for much care in the design of the SLEEP inverter, but no RFI problems to absorb a major part of the development effort.

3.8 COOLING SYSTEM AND IR SIGNATURE

The TEG uses ambient air for cooling. The unit is about 4-5% efficient overall resulting in substantial waste heat rejection. Table 8 shows the waste heat output of the TEG gas and diesel engine generators for the SLEEP family. Diesel generators of equivalent electric output ae shown for comparison. The 10-kW TEG will have a cooling system and waste heat emissions (IR) comparable to those of an 80-horsepower diesel (60-kW).

TABLE 8

ELECTRIC GENERATOR WASTE HEAT[a]
(kW)

Electric Output	TEG Heat Rejection	Gas Engine Heat Rejection	Diesel Engine Heat Rejection
0.5	12	5	–
5.0	120	45	–
10.0	250	90	40

a. Based on 4.0%, 10%, and 20% electric efficiencies for fully loaded TEG, GEG and DEG units, respectively.

3.9 ENERGY STORAGE REQUIREMENTS

The SLEEP ROC requires specified environmental operation according to AR-70-38. In accordance with these standards, the unit must provide rated power at -32°C in less than 15 minutes. Table 9 presents the estimated battery requirements for a TEG self start at -32°C; these reflect ET&DL projections of battery weights.

TABLE 9

ESTIMATED BATTERY REQUIREMENTS FOR –32°C SELF-START OF TEG'S

Unit Size (kW)	Battery Size: Phased In Start: Start (W)	Battery Size: Phased In Start: Ampere-Hours	Battery Size: Phased In Start: Weight (lbs)	Battery Size: W/O Phase In Weight (lbs)
0.5	No data	1.3	8	8
3.0	105	1.3	8	28
5.0	120	1.3	8	45
10.0	206	1.3	8	80

Source: ERADCOM [6] and Arthur D. Little, Inc., estimates.

The battery sizes were estimated by ERADCOM and, we believe, reflect the energy required to run the burner fan, pump, fuel system and electronics up to the point where the generator is producing sufficient power to power itself the remainder of the way. This is not presently done in the 0.5-kW unit and would require an integrated design effort to develop a control system capable of phasing in parasitic power during startup to minimize the battery requirement. This feature essentially permits the same 8-lb battery to meet startup requirements for the whole family with some excess capacity for the smaller unit. Without the phased-in start controls greater battery weights are required.

3.10 PHYSICAL CHARACTERISTICS

The breakdown of weights by major elements for present and future technologies are shown in Table 10.

The estimated weight of the TEG for the SLEEP family, based on present technology, is shown in Table 11. To extrapolate to higher power outputs, we estimated that the minimum weight would amount to a proportional increase in the thermopile weight plus fixed structural weight plus the foregoing weights, we have assumed a modular design in which a separate fuel system may be needed for each module.

As these estimates ignore both structural and cooling system weight increases (likely to be substantial), they represent a minimum weight that any practical unit will exceed. These minimums, shown in Table 11, clearly indicate that the TEG will exceed ROC requirements of 10-kW and is somewhat closer for the 1.5- and 3-kW units.

TABLE 10

WEIGHTS FOR PRESENT AND FUTURE TEG TECHNOLOGIES

	Present Technology (Lead Telluride)	ET & DL Projections (Silicon Ge or Selenide)
60-Hz Inverter		
(1.5 to 10-kW)	18 lbs/kW + 30 lbs	18.6 lbs/kW + 17 lbs
(500-watt)	10-15 lbs	–
Converter & Cooling System	64 lbs/kW	27.6 lbs/kW
Fuel System	5 lbs/kW	6 lbs/kW + 5 lbs
Burner & Regenerator	22 lbs/kW	
Battery	8 lbs	8 lbs
Miscellaneous	25 lbs	4.2 lbs/kW + 13.6 lbs

TABLE 11

ESTIMATED TEG UNIT SIZES AND WEIGHTS

Rated Power (kW)		ROC	TEG DC	TEG AC
0.5	Weight (lb)	80	80	92-97[a]
	Volume (ft^3)	3.5	5.1 w/Frame 3.2 w/o Frame	
1.5	Weight (lb)	150	170	227
	Volume (ft^3)	6.0		
3.0	Weight (lb)	300	305	390
	Volume (ft^3)	12.0	9	10
5.0	Weight (lb)	500	490	600
	Volume (ft^3)	18.0		
10.0	Weight (lb)	650	943	1153
	Volume (ft^3)	30.0	30	34

a. A special inverter weight relation is used for the 500-watt unit.

The additional weight required to produce alternating current, both 60 Hz and 400 Hz, will push all of the units beyond the ROC requirements. From our analysis of the present technology for AC power (see Section 3.2.2), we do not see any technique whereby the TEG-AC units will meet the ROC weight criteria.

Estimates of the TEG volume were performed by scaling the converter proportionally and the electronics by one-half the size increase. The present DC 500-watt unit with frame exceeds the ROC requirement.

ET&DL projections of the burner and regenerator weight for the newer technology are of substantial concern, as the associated converter estimate is based on 1000°C hot end temperature (presently 565°C) and a recovery rate of 83% (presently about 73%). The increased temperature and recovery efficiency is likely to result in substantial increases in the regenerator weight (rather than reductions) possibly offsetting weight losses in the converter.

4.0 APPLICATION OF A TEG TO FIELD USE

4.1 PURPOSE

In many field uses, the waste heat which is exhausted from a TEG may be used for other purposes, notably space heating and air conditioning. While fuel efficiency in producing electricity (kW/hr per gallon of fuel) may be lower for the TEG than for other power sources such as gasoline-or diesel-driven electric generators, use of the waste heat from the TEG in space conditioning may improve the overall efficiency of the system. At the request of MERADCOM, we examined the feasibility of using the TEG in an integrated energy system. This system was designed to meet the requirements of an actual field use. Different design alternatives were considered, and the most efficient prototype design was selected for comparative analysis. The performance of the TEG-integrated energy system was estimated and compared with integrated energy systems using gasoline and diesel generators for the same mission, the results of this analysis are presented in this chapter, with further details of the calculations shown in the appendix.

4.2 SELECTION OF FIELD USE FOR ANALYSIS

An existing use requiring electric power for operation of electronic equipment, plus space heating and air conditioning, was selected for the analysis. MERADCOM designated the AN/TSC-58 telegraph terminal and shelter for the purpose. The AN/TSC-58 is a shelter 12.3′ long by 7.25′ wide by 6.9′ high and is equipped with two 9000-Btu/hr compact air conditioners and electrical resistance heaters. With this configuration, the unit requires 7.176 kW of electric power for electronic equipment and space conditioning. In current field use, this power is provided by one 10-kW diesel generator or two 10-kW gasoline generators (the second gasoline generator is required for availability).

Table 12 summarizes the space conditioning requirements for the shelter at peak loads. A cooling demand was provided by Mr. Frank Good [17] of MERADCOM and used in the feasibility analysis. An electric load profile was generated by Arthur D. Little, Inc., to evaluate the design requirements for matching electric and space conditioning demands and is shown in Table 12.

A 100-hour mission was specified for the comparative analysis of the TEG and gasoline- and diesel powered systems. By specifying this standard mission, we were able to calculate the comparable amounts of fuel required for each system.

4.3 DESIGN OF TOTAL ENERGY SYSTEM USING TEG

4.3.1 Air Conditioning System

The present air conditioning load is met by two compact electric air conditioners. There are a number of techniques for meeting the space conditioning demand with generator waste heat. Two heat-driven air conditioners were considered in this study, the ejector type and the absorption type.

TABLE 12

AN/TSC-58 TELEGRAPH TERMINAL SPACE CONDITIONING AND ELECTRIC DEMANDS

Space Conditioning Demand

Heating	Btu/hr	21,738
Cooling	Btu/hr	20,429

Electric Demand

Startup	2 hrs	434 watts
Part Load	50% Mission	1600 watts
Full Load	50% Mission	2776 watts
Shut Down	2 hrs	434 watts

a. Ejector Type

An ejector type system shown in Figure 7 was selected by MERADCOM for the total energy system integrated with the TEG. The unit consists of two fluid loops. One circuit operates as a standard refrigeration cycle across a pressure differential created by the ejector loop. The ejector circuit produces the operating pressure differential with a venturi. Fluid entering the venturi experiences an increase in velocity accompanied by a drop in pressure. Refrigerant is entrained at the venturi nozzle at the low pressure. The higher system pressure developed at the ejector boiler section is maintained in the remainder of the refrigeration system (condenser, boiler liquid pump) producing the required differential pressure for refrigeration.

The efficiency and size of the unit are governed by the fluid properties, operating temperatures and the entrainment ratio achieved with the venturi design. With small entrainment values, large volumes of ejector vapor are required to move the refrigerant through the required pressure differential. This will result in the use of greater amounts of heat input required to run the refrigeration cycle and larger component elements to manage the greater vapor volumes.

Performance data, including efficiency, on the proposed ejector system were not available at the time of this writing. We have estimated the unit coefficient of performance (COP) at 0.25[18].*

*Dr. Banas under contract to MERADCOM has confirmed a COP of 0.4 at 32°C outdoor temperature and confirms a COP of approximately 0.25 at 52°C outdoor temperature.

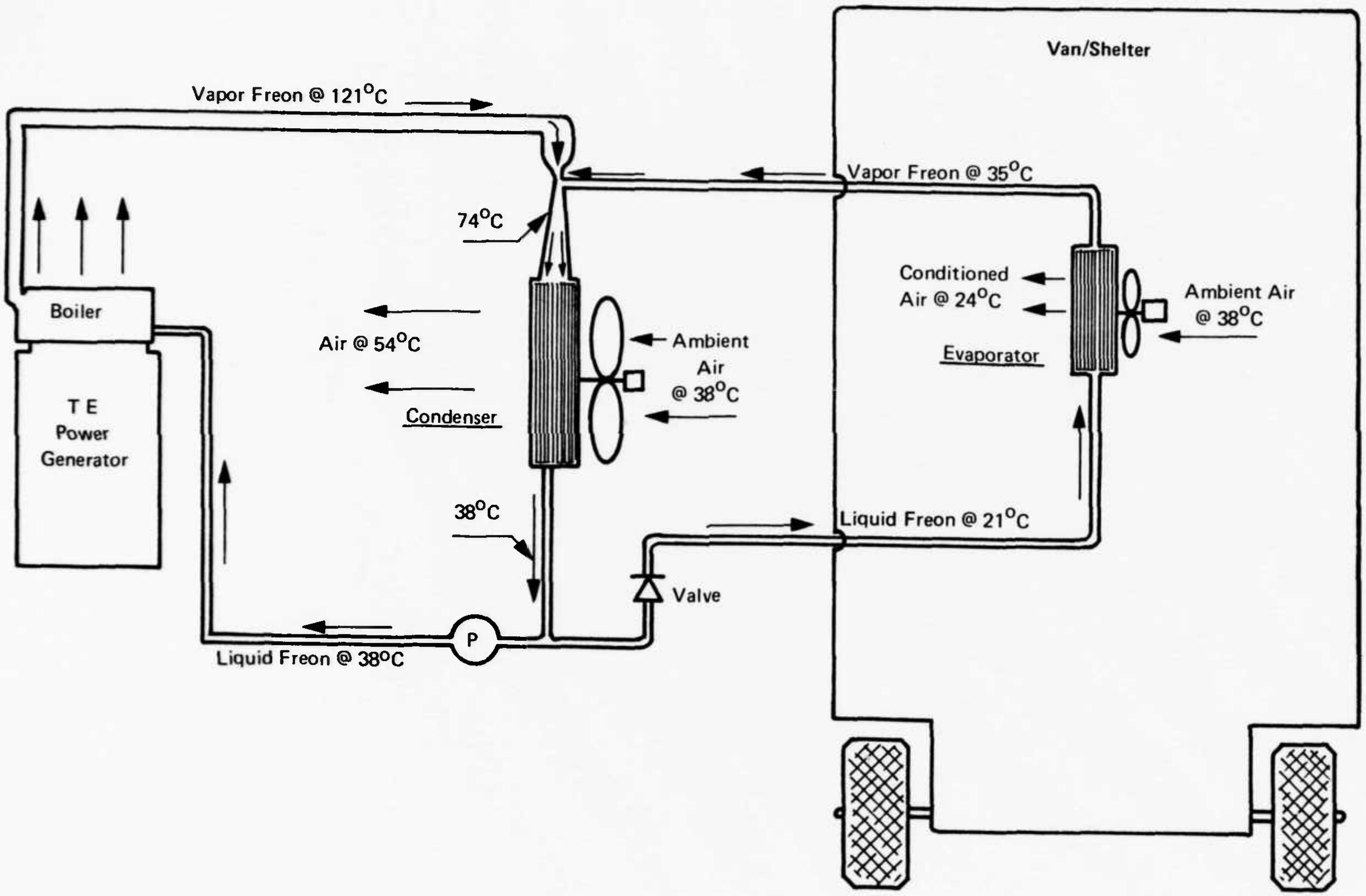


FIGURE 7 ERADCOM EJECTOR AIR CONDITIONER DESIGN

b. Absorption Type

An absorption type system could be designed for the AN/TSC-58 shelter application and would offer improved levels of efficiency for air conditioning. Arthur D. Little, Inc., has been involved in the design and analysis of a new absorption heat pump based on organic working fluids and capable of operating at the environmental conditions specified. While the design itself could provide heating at a COP greater than 1, the waste heat from the generator has been shown to be in excess of any heating demand for the shelter precluding the need for a high-efficiency heat pump for space heating. Based on analysis performed to date, a COP of 0.6 for the cooling mode could be expected with this absorption unit at some time in the future. The absorption unit will operate satisfactorily with 1000°F exhaust gas from the generator combustion process.

4.3.2 Heating System

A 1.5-kW thermoelectric generator exhausts about 58,000 Btu/hr in combustion exhaust and 77,000 Btu/hr in cooling air exhaust. Either stream will meet the maximum heating demand of 21,738 Btu/hr. However, the cooling air will be delivered at about 18° to 24°C when the outdoor temperature is -46°C at an air volume of 144 air changes per hour. This source of heat would not be satisfactory due to the high air flow and low discharge temperatures. Heat can be recovered from the combustion exhaust gas exiting at approximately 540°C. A simple clam shell type heat exchanger used in conventional warm air furnaces can be used for the heat exchanger between the products of combustion and the recirculated warm air in the shelter. Assuming a heat exchange recovery efficiency of 60%, the combustion gases can still provide 200% of the maximum heating demand.

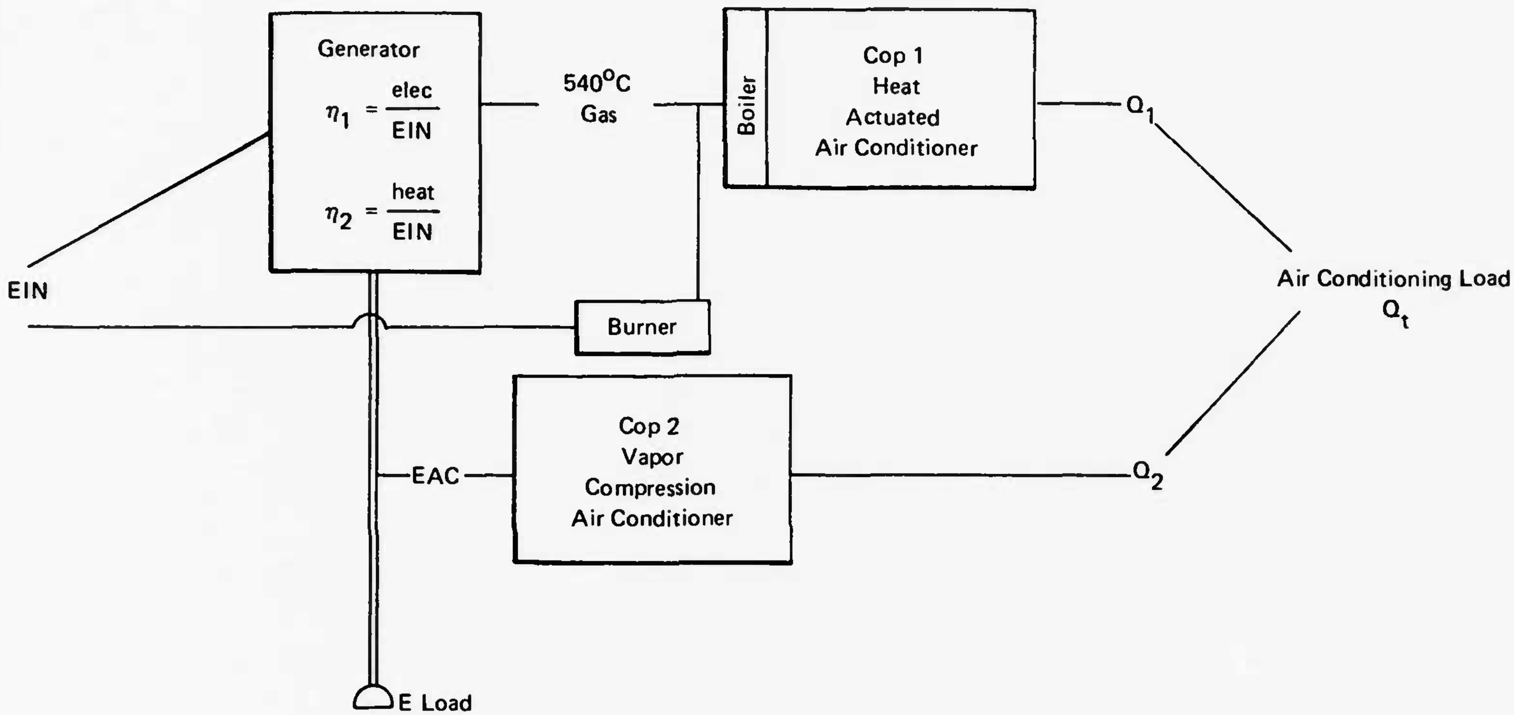
4.3.3 Summary

Electrical demand for operation of the electronic equipment contained in the AN/TSC-58 can be met by a 3-kW TEG. While the cooling air from the thermopile is not sufficient for space heating in very cold climates, a secondary heat exchanger used in conjunction with the products of combustion from the 3-kW TEG can provide all necessary space heating requirements. Because the TEG operates at full heat output independent of electric demand, a heat driven air conditioner using waste heat from the 3-kW TEG is sufficient to meet cooling needs. An absorption air conditioner was used for the design in the analysis.

4.4 DESIGN OF TOTAL ENERGY SYSTEM USING GAS/DIESEL GENERATOR

The focus of the system analysis is the application of the TEG to the AN/TSC-58 shelter in a total energy configuration. For comparative purposes, similar systems based on existing gas and diesel generators were analyzed.

A generalized system for providing electric power, space heating and cooling was designed for this study and is shown in Figure 8. This system was used to analyze the operation of a TEG, a gasoline generator, and a diesel generator in a total energy system to supply the heating and cooling electric demand needs of the



where

E Load	=	Electric load for telegraph terminal (lights and telegraph)
EIN	=	Energy input from fuel
EAC	=	Energy consumption of vapor compression air conditioner
Cop	=	Coefficient of performance (cooling rate/power input)
Q_1	=	Air conditioning from heat actuated air conditioner
Q_2	=	Air conditioning from vapor compression air conditioner

FIGURE 8 GENERALIZED TOTAL ENERGY SYSTEM

AN/TSC-58 shelter. The operation and key assumptions are discussed in the following paragraphs.

We have assumed that waste heat from the gasoline engine and that from the diesel engine are approximately 540°C and are sufficiently clean to operate the boiler section of the absorption or ejector air conditioner (a considerable problem with diesel exhaust).

During periods of low electric power demand, waste heat output from the generator will be reduced if the generator follows the electric load. Under this condition it may no longer provide sufficient heat to the heat-driven air conditioner too meet the air conditioning demand. The air conditioning deficit can be met by supplementing the heat input to the heat-driven air conditioner with an auxiliary burner as shown in Figure 8, or by operating an electric air conditioner in parallel. Using an electric air conditioner to augment the cooling generates additional waste heat from the electric generator, simultaneously to increasing the heat-activated air conditioner output.

Through design analysis of the systems described, we have found that an auxiliary electric air conditioner is desirable for augmentation to the diesel generator though not for the gasoline and thermoelectric generators. We have found that burner augmentation of the heat-driven air conditioner used with the gasoline generator is the most fuel-conserving mode of operation for the gasoline generator integrated system because of the rather poor electric efficiency of the gasoline generator.

4.5 COMPARISON OF TEG AND GAS/DIESEL GENERATORS

4.5.1 Field Use Profile

For purposes of the analysis, we selected a mission of 100 hours. Climate conditions for the duration of the mission were assumed to be equal to hot climatic design profile as given in AR 70-38. The electric load for the operation of electronic equipment varied from startup to peak loads of 2,776 watts and is shown in the Appendix (A.3.4).

4.5.2 Critical Variables in the Analysis

In addition to the key thermal characteristics needed to analyze the system performance and the space conditioning and electric demands of the shelter shown in Figure 8 and Table 12, respectively, the following additional values were used in the analysis.

Electric Generator Efficiency at Full Load (%)

10 kW Gas	= 10
3 kW TEG	= 5*
10 kW Diesel	= 20

*A 5% overall efficiency is assumed for a new 3-kW unit with maximum regenerator heat recovery (82%); 7% thermopile efficiency, a 90% efficient AC inverter, and a high-efficiency cooling fan/motor (60%).

Ratio of Heat Rejection to Heat Input of Generator (%)

Gas	= 30
TEG	= 40
Diesel	= 30

4.5.3 Method of Analysis

The integrated energy systems with each generator (TEG, gasoline, diesel) were analyzed by calculating fuel use on an hourly basis for the duration of 100-hour mission and then by adding the individual hourly steps to determine total fuel consumption. Calculations were done using both vapor compression and absorption air conditioners.

4.6 FEASIBILITY OF TEG/TOTAL ENERGY SYSTEM FOR THE AN/TSC-58 SHELTER

A preliminary analysis of the TEG in a total energy system indicates that the 3-kW TEG with an absorption air conditioner can meet the space conditioning and electric requirements of the AN/TSC-58. Table 13 shows the estimated weight and size (in cu ft) of a 3-kW TEG system compared to that of a 10-kW diesel generator in combination with conventional air conditioners. The TEG/Total Energy unit would weigh 615 pounds less and occupy 18 less cubic feet than the diesel-based system.

Cost estimates have been made of several components in these systems. The air conditioner costs are retail costs since military costs were not available for the absorption unit. Cost estimates for the generators (TEG and diesel) have not been provided by ERADCOM at this writing.

Table 14 gives the predicted fuel consumption for a 100-hour mission of the TEG, gasoline and diesel total energy system. Table 15 lists the estimated system weight and volume including fuel.

TABLE 13

FEASIBILITY OF TEG/TOTAL ENERGY SYSTEM

	3-kW TEG/Absorption A/C			10-kW Diesel/Vapor Compression A/C		
	Weight (lbs)	Volume (cu ft)	Cost ($)	Weight (lbs)	Volume (cu ft)	Cost ($)
Generator & Inverter	390	10	X	1240	43	X
Air Conditioner						
• Vapor compression air conditioner (2-9,000 Btu/hr units)	X	X	X	260	9	X
• Absorption air conditioner including condenser	491	24	3000	X	X	X
Heater (10,000 Btu/hr)	Not Needed	0	100	X	X	X
Indoor Fan & Ducts	4	Uncertain	50	X	X	X
SYSTEM SUBTOTAL	885	34	X	1500	52	X
As % of AN/TSC-58[a] (w/o air conditioners)	18%	5.5%	X	30%	8.4%	X
Fuel	918	20	X	652	13	X
TOTAL	1803	54	X	2152	65	X

a. AN/TSC-58 weighs 4940 pounds without the air conditioners.

TABLE 14

COMPARISON OF FUEL CONSUMPTION (GAL) IN A 100-HR MISSION

Configuration	TEG		GEG		DEG	
	3-kW	10-kW	3-kW	10-kW	5-kW	10-kW
Absorption	153	X	84	X	54	X
Ejector	158	X	122	X	X	X
Ejector & Vapor Compression	X	X	X	X	74	X
Vapor Compression	X	426	X	241	X	98

TABLE 15

COMPARISONS OF SYSTEM SIZE INCLUDING FUEL
(Includes power unit and fuel for 100-hour mission)

	TEG			GEG		DEG	
Volume (cu ft)	**3-kW**	**(2)3-kW**	**10-kW**	**(2)3-kW**	**(2)10-kW**	**5-kW**	**10-kW**
Absorption	55	66	X	60	X	67	X
Vapor Compression	X	X	100	X	97	X	65
Weight (Lbs)[a]							
Absorption	1803	2300	X	1559	X	1775	X
Vapor Compression	X	X	4043	X	3406	X	2152

a. AN/TSC-58 weighs 5300 pounds with air conditioner.

5.0 FINDINGS AND RECOMMENDATIONS

5.1 FINDINGS

With regard to the TEG as a candidate for the SLEEP application and based on demonstrated and predicted performance of the current 500-watt TEG units, we find that the 500-watt TEG meets the SLEEP ROC except that:

- The 500-watt AC TEG unit will exceed the weight criteria by 10-20%, and

- Maximum demonstrated reliability is about one-third of the requirement, though the projected reliability of the Global 6.3 model will exceed the requirement.

Based on projections of the current technology to 1.5- and 10-kW applications, we find that the TEG will meet the SLEEP ROC except that:

- The 10-kW AC unit will exceed the 650 pounds weight requirement by 500 to 600 pounds. Lower power units exceed the requirement but by proportionally less.

- The 10-kW unit will exceed the noise inaudiability requirement of 20 dB by 23 dB.

With regard to the application of the TEG in the example AN/TSC-58 total energy application, we find that:

- A 3-kW TEG/Total energy system can meet the energy requirements of the shelter presently met by a 10-kW diesel, or two 10-kW gasoline generators.

- The 3-kW TEG/Total energy system weighs 41% less than a single 10-kW diesel engine/air conditioner system and occupies about 35% less space (cu ft). It weighs 55% less than two 10-kW gasoline generators and occupies 48% less space.

- Successful operation of the 3-kW TEG/Total energy system will depend on fielding a reliable TEG and heat-actuated air conditioner.

- A 3-kW TEG/Total energy system uses about 56% more fuel than the present single 10-kW diesel/electric air conditioner but offers a 37% reduction over two 10-kW gasoline generator/electric air conditioners.

5.2 RECOMMENDATIONS

Based on the brief analysis of the TEG performance to date, we recommend:

- The SLEEP ROC weight and size requirements should be reviewed and revised to encourage optimum design trade-offs using the most recent technology. Consideration should be given to relaxing the acoustic (silent) requirement for larger units.

- The Army should consider a mix of technologies for the SLEEP application, possibly targeting silent, less fuel efficient units (TEG) for small sizes (0.5-3 kW) and more fuel efficient units for larger applications to 10 kW.

- Specific reliability, availability and maintainability criteria should be established for the ROC.

- Operational testing of the Global 6.3 model should be undertaken with a focus on availability and transportability.

- Acoustic design and electronic controls improvement should be implemented for the current model.

- A design study followed by a feasibility test of total energy AN/TSC-58 system should be undertaken. Attention should be given to the design of the interconnection of components and to detailed component sizing and controls specifications.

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APPENDIX

SUPPORTING DATA FOR TOTAL ENERGY SYSTEM ANALYSIS

A.1 AN/TSC-58 — Total Energy System — Analytic Approach

Fuel consumption was calculated on a hour-by-hour basis, using the part load data (A.2.1.2), shelter heat load (A.2.2.3) and electric load profiles (A.2.2.4). This was accomplished by first calculating the amount of waste heat from the generator using the electric load profile (A.2.2.4) and heat rejection ratios (A.2.1.3). If the waste heat is sufficient to power the absorption unit to meet the air conditioning demand (aborption unit coefficient of performance COP = 0.6), then the fuel consumed is only that required to meet the electric load. When the electric generator waste heat is not sufficient to meet the air conditioning demand alone, an auxiliary burner, or auxiliary electric air conditioner (Figure 8), is considered, and the least-fuel-consuming approach is used. See Section 4.2.4 for further discussion of this aspect.

Auxiliary power (if needed) to meet the air conditioning load is calculated and added to the generator demand to determine the total fuel consumed each hour.

A.2 Technical Data for AN/TSC-58 Shelter Calculations

A.2.1 Gas and Diesel Generator Data

A.2.1.1 Fuel Data

Gasoline: Density 6 lbs/gal; heating value = 20,700 Btu/lb

Diesel: Density 6.6 lbs/gal; heating value = 19,500 Btu/lb

Source: *Marks Standard Handbook for Mechanical Engineers*, 8th Edition, 1978.

A.2.1.2 Performance Versus Load Percentage

	Gasoline 10-kW Electric Generator		**Diesel 10-kW Electric Generator**	
Load in Percent	**Efficiency (%)**	**Fuel Consumption (lbs/hr)**	**Efficiency (%)**	**Fuel Consumption (lbs/hr)**
Idle	0	10.5	0	4.6
25	4	11.6	8	5.3
50	6	13.2	14	6.3
75	8	15.3	18	7.3
100	10	16.8	20	8.7
125	11	18.6	23	9.7

Efficiency = Electric Output/Fuel Heating Value Input

A.2.1.3 Ratio of Heat Rejection to Heat Input (%)

TEG	40
Gasoline Generator	30
Diesel	30

A.2.2 AN/TSC-58 Technical Characteristics

A.2.2.1 Power Requirements (115V, AC, 60 Hz, Single Phase)

Lights (Fluorescent 384 watts and Incandescent 50 watts)	434 watts
Power Distribution Panels	8 watts
Transmitter, Teletypewriter, Security Equipment, Low-Level Signaling Device, Intercommunication Station, Miscellaneous	2334 watts
Subtotal	2776
Two Air Conditioners	4400
Total Demand	7146 watts

A.2.2.2 Mechanical Characteristics

Dimensions:	
Length	
Without Air Conditioner	147 inches
With Air Conditioner	157 inches
Width	87 inches
Height	83 inches
Weight:	
Total	5340 lbs
Without Air Conditioners	4950 lbs

A.2.2.3 Shelter Heat Load Characteristics

Hour	Shelter Heat Load, Including Internal Heat (Btu/Hr)
0-6.5	14,000
6.5-7.5	14,800
7.5-8.5	16,700
8.5-9.5	18,100
9.5-10.5	19,200
10.5-11.5	19,900
11.5-12.5	20,400
12.5-13.5	20,100
13.5-14.5	19,600
14.5-15.5	18,700
15.5-16.5	17,800
16.5-17.5	16,800
17.5-18.5	15,700
18.5-19.5	14,100
19.5-24	14,000

Source: F. Good Personal Communication, "Heat Load Analysis of AN/TSC-58 Shelter," June 1981.

A.2.2.4 Assumed Electric Load Profile

2-hour set up requiring only lights — 434 watts

Repeating 4-hour cycle of 2 hours at part load (1600 watts and 2 hours at full load (2776 watts)

2 hours of shutdown requiring only lights — 434 watts

Source: Arthur D. Little, Inc., estimate.

A.2.3 Summary of Weights and Sizes

*A.2.3.1 Thermoelectric Generator**

	Weight (lbs)	Volume (cu ft)
3-kW TEG	390	10
absorption A/C unit	495	24
Fuel (153 gal)	918	20
Total	1,803	54
3-kW TEG	390	10
ejector A/C	215	30
Fuel (158 gal)	948	21
Total	1,553	63
10-kW TEG	1,153	34
vapor compression A/C	334	9
Fuel (426 gal)	2,556	57
Total	3,969	100

*Miscellaneous weights and volumes for ducts and heaters are included in all of the air conditioner entries.

A.2.3.2 Gasoline Electric Generator

	Weight (lbs)	Volume (cu ft)
2 ea 3 kW GEG @ 280 lbs ea	560	24
Absorption A/C	495	24
Fuel (84 gal)	504	12
Total	1,559	60
2 ea 3 kW GEG @ 280 lbs ea	560	24
Ejector A/C	210	30
Fuel (122 gal)	732	16
Total	1,512	70
2 ea 10 kW GEG @ 813 lbs ea	1,626	56
Vapor Compressor A.C	334	9
Fuel (241 gal)	1,446	32
Total	3,406	97

A.2.3.3 Diesel Electric Generator

	Weight (lbs)	Volume (cu ft)
5-kW DEG	920	35
Absorption A/C	495	25
Fuel (54 gal)	360	7
Total	1,775	67
10-kW DEG	1,166	43
Vapor Compression A/C	334	9
Fuel (98 gal)	652	13
Total	2,152	65

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